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THE MEASUREMENT AND STATISTICAL MODELING OF COMPUTER RELIABILITY
AS AFFECTED BY SYSTEM ACTIVITY

Edward J. McCluskey and Dorothy M. Andrews

FINAL REPORT

November, 1985

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Contract No. DAAG29-82-K-0105

CENTER FOR RELIABLE COMPUTING
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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FINAL REPORT

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Keywords: Reliability Modeling; Failure/Load Relationship; Failure Prediction; Fault Tolerance; Computer Utilization Rates; Error Detection; Error Correction.

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1 INTRODUCTION

This report describes the research findings of a three year study that included the measurement and statistical modeling of computer reliability as affected by system activity. The ultimate aim of this research has been to develop fundamental concepts that can be used to increase the reliability, availability, and throughput of computer systems. During this three year period, the major research findings have been the following:

* Established existence of a failure/load relationship, that is, the more a computer is used, the more it fails [Sec. 2].

* Demonstrated the effect of more complex program interactions (which result from an increase in data processing) as a major cause of computer failure [Sec. 3].

* Identified major problem areas in software error types (deadlock, data management, and error handling) where improvements in system recovery or fault tolerance should be made [Sec. 3].

* Demonstrated the effect of electro-mechanical device failures as a subtle, but significant influence on software failures [Sec. 3].

* Identifed device level failure mechanisms as explicit causes of failures that are due to heavy usage [Sec. 4].

* Demonstrated that not only the amount of activity, but also the

type of activity affects the reliability of computer systems [Sec. 5].

* Established existence of change in error distributions and/or activity rates prior to a crash. This change could provide a basis for development of a technique for prediction of computer failures [Sec. 6].

The research findings are discussed in more detail in Sections 2-6. The appendix contains a list of publications during the three year period, as well as a list of participating scientific personnel.

2 ESTABLISH FAILURE/LOAD RELATIONSHIP

The failure/load relationship was established by statistical analysis of data collected over a period of eight years from three generations of computers. These computers were installed at two different physical locations and were dedicated to different types of applications. To establish the dependence of system failures on the amount of activity or load on the system, comparisons were made between the different generations of computers, as well as between identical computers running different applications.

2.1 PRIME TIME VS. SYSTEM CRASHES

Initial interest at Stanford University in the relationship of utilization level and system reliability began with the study of [Beaudry 78] which developed a model for failure of computing systems with varying workload. The model was based on statistical analysis of data from a Triplex multiprocessor at Stanford Linear Accelerator Center (SLAC). This system used three separate central processing units (CPUs): two IBM System/370 Model 168s and an IBM System/360 Model 91. First it was found that a disproportionate number of service interruptions (system failures) occurred during prime time when system utilization is higher. The results are shown in Table 2.1. Then system failures and job arrivals were compared, and the statistical evidence also pointed to a definite relationship between heavy demand on system resources and the system failure rate. As a result of this study, it became clear that a constant failure rate was no longer valid in a fluctuating load environment. (This was confirmed later by [Castillo 80,81] at Carnegie-Mellon University.)

Table 2.1. Higher crash frequency during prime time.

Source of System Failure	Number Occurring During Prime Time	
All	239	62%
Software	155	68%
Hardware	58	60%
Miscellaneous	23	44%

2.2 ANALYSIS OF ADDITIONAL FACTORS IN RELIABILITY

A subsequent study was performed on UNILOG data from the same Triplex multiprocessor at SLAC, but additional factors were analyzed in order to more accurately evaluate system reliability [Butner 80] [Iyer 82a]. Not only did this analysis seek to find more indicators of system load than just job arrivals, but it also analyzed more types of failures than just those failures which caused service interruptions or brought the system down.

Overall computer load is a multi-dimensional quantity with many parameters that indicate utilization. Some of these affect the failure rate more than others. System utilization and performance data was analyzed, and it was found that paging was the strongest single utilization factor related to failures. An increased level of concurrency implies an increased usage of hardware and software paths, so it was not unexpected to find a strong relationship between paging and failures for hardware and a similar, but less strong, relationship for software. A profile of paging at SLAC is shown in Figure 2.1 and component failure profiles for hardware and software in Figure 2.2.

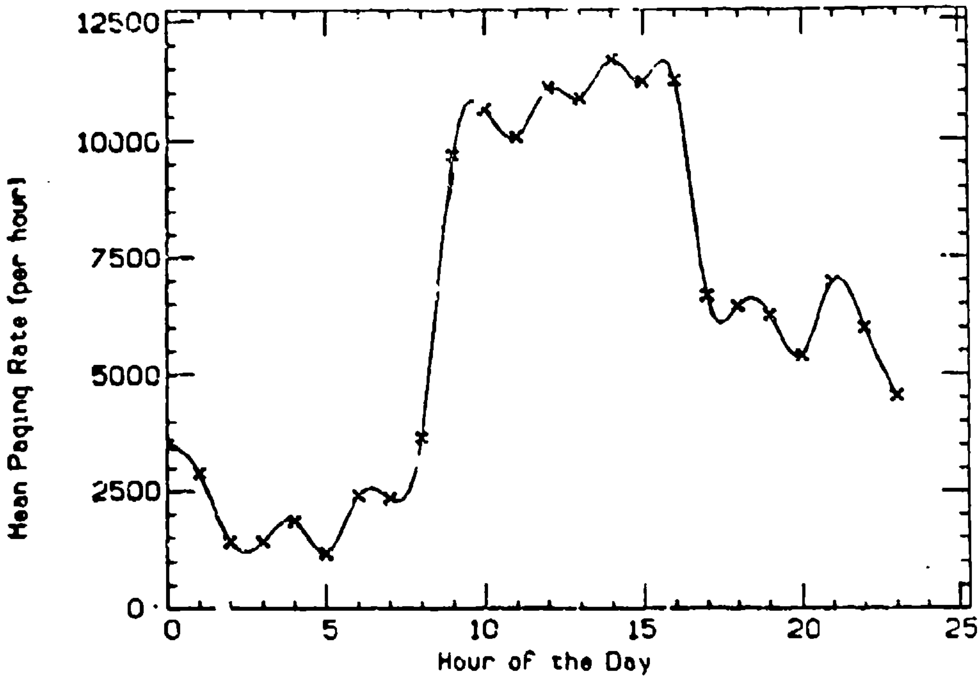

Figure 2.1. Paging profile.

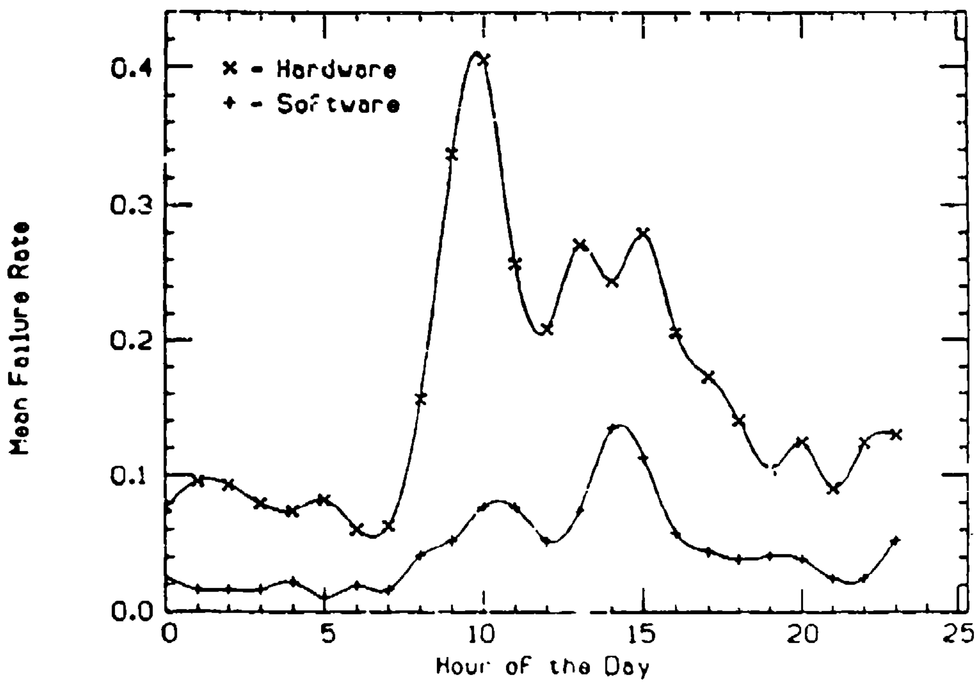

Figure 2.2. Component failure profiles.

2.3 FAILURE/LOAD RELATIONSHIP ON DIFFERENT COMPUTERS

Since these preliminary studies showed a correlation between failures and system utilization, it was necessary to demonstrate whether this correlation would exist for other computers and other computing environments. Consequently, a comprehensive statistical analysis was made on data collected on an IBM 3033 which was installed on the Stanford University campus at the Information Technology Services (ITS, formerly known as CIT) [Iyer 82b]. Differences in computer redundancy and applications which exist at this facility made it a good choice for comparing data from ITS with that of the SLAC facility. Fortunately, the reports generated by the SLAC and ITS systems contain similar information. System utilization data came from the IBM System Management Facility (SMF) records, and the failure data came from the operator-maintained database called UNILOG. This data was examined for the same three years at both locations.

The preliminary study showed that all system failures correlated with load, therefore, it was important to determine whether this was true for different components off a system, as well as the system as a whole. The frequency of failures for different component and usage groups for both systems revealed a strong statistical dependency of component failure rates on several common measures of utilization (CPU utilization, I/O initiation, paging, and job-step initiation rates.) This relationship existed for electrical and mechanical, as well as software components [Iyer 82b].

Comparisons between the two systems revealed interesting differences: for example, although SLAC components were older and were more prone to failure than those at ITS, the SLAC system was more reliable (MTBF 23.2 hours vs. 17.7 at ITS). This was attributed to the fact that at SLAC a great deal of the computational load was served by processors that act as batch stream servers. Failures within these machines do not affect the rest of the system, which accounts for the relatively high fault tolerance of the SLAC facility.

2.4 MACHINE AND MANUAL RECORDED FAILURE DATA SUBSTANTIATION

So far in these studies, failure data had been obtained from manually recorded files. However, there is an automatic recording of hardware and software errors in a log, called LOGREC. Since some of these errors are corrected by retry or redundancy, their presence would remain unknown except for the record in LOGREC. To obtain further verification of the failure/load relationship by looking at the internal behavior of the machines, the next study used a portion of this machine-collected data on failures (CPU errors) and correlated it with workload data from the usual source (SMF) and from a software monitor [Rossetti 82].

The purpose of the monitor, which was written especially for this project, is to obtain detailed information about transient behavior in the CPU. The reason it was important to examine the CPU error generation process is that a large portion of these errors were suspected of being transient or intermittent and very little was known about their behavior. The study showed that 95% of the CPU errors were "soft" errors, that is, those from which the system recovered, and that these errors also exhibited a dependency on system activity. (Nearly 90% of field errors are believed to be of this type [Ball 69].) By merging the error data with the load data, development of a load-hazard model for CPU errors was possible. The model was validated by seeding errors in an artificially created data base. Details of the experiment and of the monitor may be found in [Iyer 83a]. Measurement and modeling of hard CPU failures and system activity is described in [Iyer 84b].

2.5 CONFIRMATION BY DATA FROM A THIRD MAINFRAME

A subsequent analysis performed on software failure data from a third type of mainframe (an IBM 3081) provided further confirmation of the failure/load dependency [Rossetti 82]. Figure 2.3 shows a histogram of software failures by hour of day from the accumulated data analyzed. This study also demonstrated that the risk of software-related failure increases in a non-linear fashion with the percentage of interactive processing (as measured by parameters such as the paging rate, system overhead, etc.). This was the first indication that, not only the amount of system activity, but also the type of system activity influences the reliability of computers. The software errors most frequently identified with system failures fell into three major categories: error handling, logic, or hardware-related. It is interesting to see that errors in the code which provides fault tolerance in the form of exception handling built into the software is in itself a frequent cause of errors.

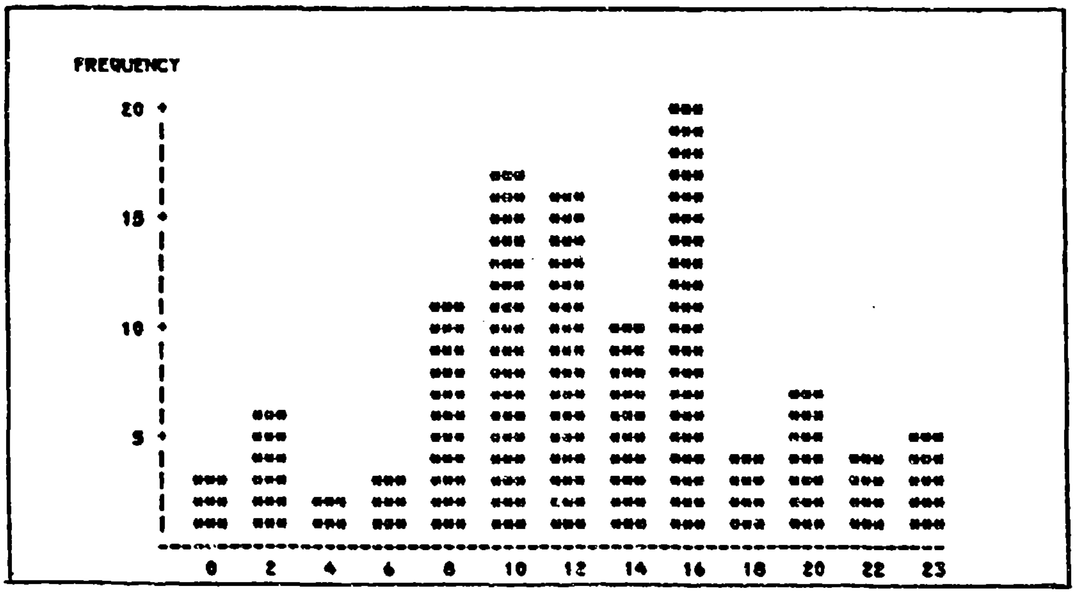

Figure 2.3. Accumulated software failures by hour of day.

3 ANALYSIS OF SOFTWARE ERRORS AND FAULT TOLERANCE

The motivation for this study came from the analysis by [Beaudry 77-79], which showed that software errors account for more system failures than hardware errors, and by [Rossetti 82], which delineated the software errors by type and identified those most frequently associated with system failures. The aim of this part of the research was to assess the fault tolerance provided by the computer system and to identify those areas where recovery procedures were ineffective.

All software errors detected by the operating system were classified according to error type and then statistically analyzed for error frequency, effectiveness of error recovery routines, and fault tolerance provided by the software. (Error classification reports that were used in this study are [Endres 75], [Gannon 83], and [Thayer 76].) The results showed that memory allocation or addressing, along with deadlock problems, accounted for 75 percent of all software errors. From the analysis of the system error detection and correction capabilities, estimates were made of the fault tolerance to errors of different types. The information revealed by this study [Velardi 84] pinpoints major problem areas, i.e. deadlock, I/O and data management, and exceptions, where improvement in the system recovery should be made.

In a second study [Iyer 84c], hardware and software interaction was examined, with particular emphasis on detection and correction of software errors that are related to temporary and permanent hardware problems. It was found that recovery from hardware-related software errors is less likely than from other software errors. The statistical information about error patterns will be invaluable in developing detection and recovery schemes for hardware-related software errors, since the specific questions of the interaction between hardware and software is a subject that has not received careful study in the past.

4 FAILURE MECHANISMS AND UNCERTAINTY FACTORS

To better understand the factors that cause the increase in hardware failures when system activity increases, the effects of the switching rate on device reliability were studied. It was found that the higher the system activity, the greater is the risk of failure due to thermal effects and electromigration at the device level [Cortes 84].

Programs for calculating the reliability of fault-tolerant systems do not explicitly take into account the effect of failures in the hardware switching mechanism. Incorporation of switch failures in reliability modeling of redundant systems was studied and is outlined in [Amer 86]. Another study showed that, due to the effect of uncertainty in failure rates, memory unreliability increases and may even double in very highly reliable systems [Iyer 83b]. As a result of these findings, the possibility of developing suitable techniques which incorporate an uncertainty factor in failure rate estimations should be investigated.

5 FACTORS AFFECTING OPERATING SYSTEM RELIABILITY

One objective of this study was to follow up and expand the investigations reported in [Velardi 84] and [Iyer 84c,85]. This decision was made because the IBM 3081 used in these studies was upgraded to a Model K (with installation of additional hardware) and was running under a newer operating system, the MVS/XA. In addition, the study was expanded to include data from another identical computer, not previously monitored, which had an entirely different type of utilization. In this way, two major comparisons could be made. First, the two IBM 3081 systems running under MVS/XA were compared to show how the type of utilization affects their software and hardware error behavior. Second, new data from the system previously monitored were compared to those reported for the same system when it was running under the MVS/SP operating system [Velardi 84]. Full results of this study are reported in [Mourad 85a,b].

5.1 COMPARISON OF TWO TYPES OF UTILIZATION

The results of this analysis definitely showed there was a dependency of system errors on type of system utilization. One system studied is used mainly to run an interactive program to update library acquisitions. The errors encountered with this system were related to disk problems and storage management. The second system has a varied utilization that includes: word processing, statistical packages, administrative, and research programs. Deadlock and addressing exceptions were the major problems reported. The errors of the first system reflect the uniform use of one major interactive program, while the errors of the second result from the more varied usage.

5.2 COMPARISON BETWEEN TWO OPERATING SYSTEMS

By comparing the performance of the same computer under MVS/SP and under MVS/XA, the following conclusions were made:

* Deadlock and I/O managment were still the main problem areas for the recovery system.
* Storage exception errors are more frequent under the newer MVS/XA operating system and is probably due to the bimodal addressing implemented on MVS/XA.
* Software errors are still more frequently detected by software than by the hardware.
* Lost records are definitely fewer which indicates a more reliable system for recording errors.
* The MVS/XA system is more fault tolerant than the MVS/SP.

6 FAILURE PREDICTION

Failure prediction provides a new and innovative direction toward improving system reliability and availability. It is a crucial factor in providing failure prevention and system fault tolerance. (Preliminary work in this area has also been started at Carnegie Mellon University [Siewiorek 84].) The problem is that a reliable basis must be found on which to make a prediction. During investigation of the effect of system activity on computer systems reliability, however, it became apparent there was an increase in the number of errors immediately before a crash. As a result of this observation, research on the possibility of predicting failures (based on a prior increase of errors) was started.

A statistical analysis was done on all categories of hardware and software errors automatically recorded by the IBM 3081 system at ITS for a period of six months. The results show that the rate of generation of certain errors, namely those from failing disk drives and pending interrupts, appears to increase monotonically right before the occurrence of a crash and, therefore, might be used to predict a crash in advance. However, other error types have an abrupt increase of errors before a crash (and display no discernable pattern) but may indicate certain threshold characteristics that would be useful in failure prediction. Figure 6.1 shows a histogram of the monotonic increase in errors before a crash, and Figure 6.2 shows an abrupt increase. The interval of time in both histograms is from the time the system was last started to the time of the crash.

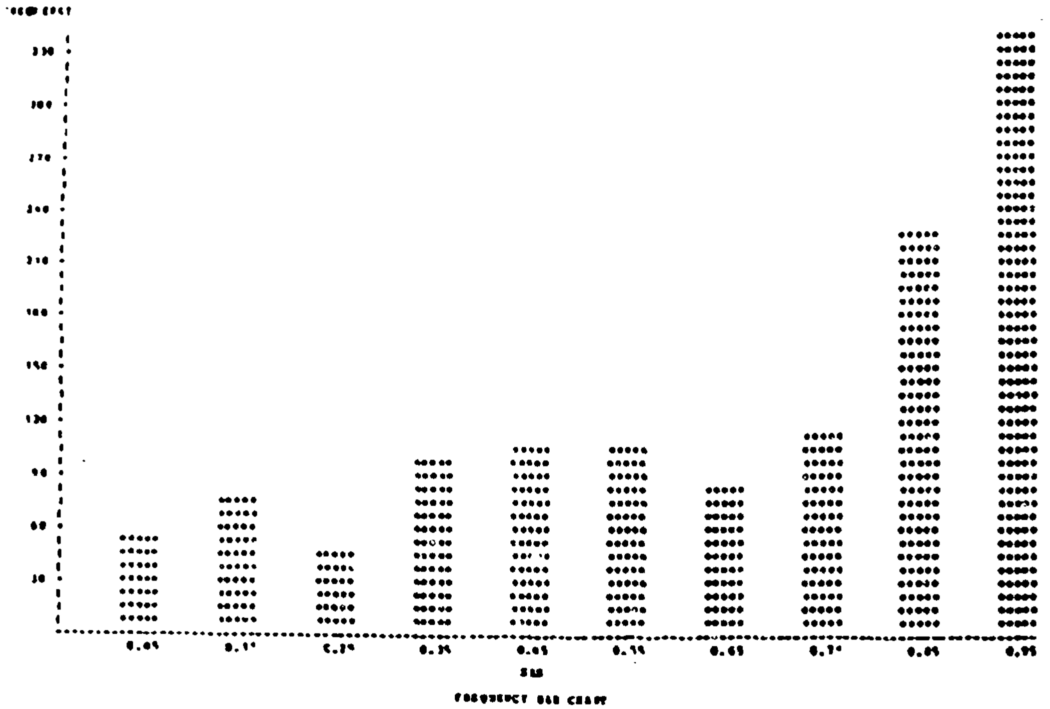

Figure 6.1. Monotonic increase in errors before a crash.

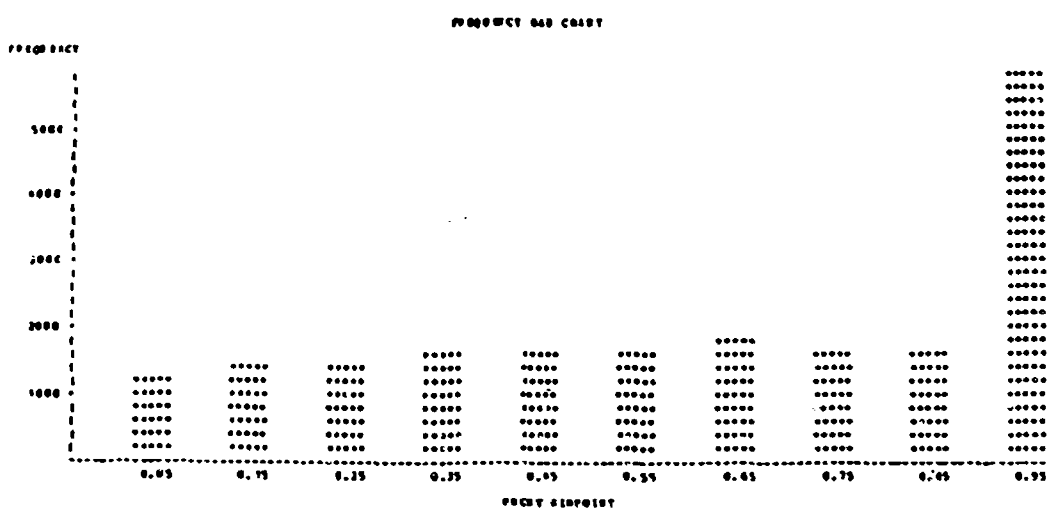

Figure 6.2. Abrupt increase in errors before a crash.

Details of the methodology for analysis of failure prediction data developed during this research have been reported in [Nassar 85a,b]. The first step of the methodology was to characterize a d cluster crashes to find appropriate intervals of time to analyze between system restart and a crash. The next steps involved averaging and weighting error distribution data, analyzing individual intervals between crashes, and analyzing CPU utilization rates prior to crashes. The results of the analysis demonstrated that there are certain recurrent patterns in the distribution of errors before a crash. In addition, analysis of system utilization rates prior to a crash indicated existence of a relationship between high utilization and frequency of system failures. These preliminary results indicated that failure prediction based on a combination of one or more of these factors may be feasible.

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APPENDIX

FINAL PUBLICATION REPORT

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